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AN INITIAL EVALUATION OF A VIBROTACTILE DISPLAY IN COMPLEX CONTROL TASKS

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FOREWORD

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<u>AN INITIAL EVALUATION OF A VIBROTACTILE DISPLAY IN COMPLEX CONTROL TASKS</u>

The initial phases of an interplanetary space flight can be expected to place the human under a considerable amount of environmental stress. High G-forces resulting from rapid acceleration, for example, are known to disturb a number of physiological processes. To the extent that such stressful conditions reduce the capability of the human to perform normally the functions required of him in the vehicle, ways must be found to adapt the machine components to human limitations under these adverse conditions.

Whatever man's part may be in the control of the vehicle, it is probable that he will receive and process some form of sensory input information on the position of the vehicle in space. Under normal circumstances the visual sense channel is most frequently used for this purpose. Unfortunately, the visual system is one of those most adversely affected by environmental stresses such as G-forces (7). Therefore, the problem arises as to the best method of overcoming this visual sense deficiency. The approach taken in the present research was that of considering an additional sensory system which might be used as a substitute for the visual system under high G stress conditions. For a number of reasons discussed elsewhere (2), as well as its probable resistance to G effects, the tactual system appeared to be the only possibility worthy of investigation. In the studies described below, therefore, a systematic attempt was made to determine how adequately the tactual system might serve in performing certain functions normally assigned to vision.

Several reports have appeared recently which demonstrate the capability of the tactual system to decipher information encoded into <u>discrete</u>, multidimensional vibratory signals (2, 3). The present interest, however, was in the control of <u>continuous</u> signals using the vibrotactile display mode, a task more similar to those encountered in vehicular control.

In all, three investigations were undertaken. The first was concerned with the general feasibility of the vibrotactile system as a display channel and with the determination of parameters of particular interest for further investigation. In this work three compensatory displays were compared under conditions considered to be least favorable to the tactual mode. The displays were (a) an optimum visual situation providing continuous display of the error between input and response signals, (b) a discrete, three-element visual display indicating only on-target and directional error information, and (c) a vibratory analog of the discrete visual display. The second study was an extension of the first to a situation more nearly approximating the machine dynamics expected in the initial phases of interplanetary space flight. Specifically, the display comparisons were made under two levels of aiding in a second-order control system: quickening and quickening plus display-aiding (superquickening) (1, 6). In the third study an attempt was made to determine the feasibility of a vibratory display in which apparent movement (the so-called "phi effect") was used to indicate direction of system error.

EXPERIMENT I

The first experiment, like the second and third, was conducted under normal 1-G conditions. The over-all goal of the three studies was to examine a display mode which could be effective under high G conditions. However, prior to test under such conditions it was felt desirable to examine the vibrotactile display in a stress-free environment with the understanding that should the vibratory display be ineffective in these "ideal" conditions, further investigation, as in a centrifuge, would not be necessary.

Method

Subjects.—Two members of the Laboratory staff served as subjects (Ss). Both had had previous experience with visual tracking tasks in the Laboratory.

Apparatus.—The Ss attempted to null error through Type 0 or positional dynamics in a one-dimensional tracking task. Control signals were generated by S via a spring-centered control column, and S received information on system error via one of three displays: a continuous visual display, a discrete three-element visual display, or a discrete three-element vibrotactile display. The continuous display consisted of a fixed reference line and a partially overlapping cursor line on a cathode ray tube. The position, velocity, and accelerations of the cursor reflected comparable information on system error. The discrete visual display consisted of three 6-v. lamps arranged in a horizontal line. When the effects of S's controlling responses resulted in near-zero system error (on target) the center light was automatically actuated; an error to the "right" caused the center light to be extinguished and the right lamp was actuated; and an error to the "left" actuated the left lamp. The discrete vibrotactile display consisted of three independent, mechanical vibrators mounted in a harness and arranged in a horizontal line 7 in. apart on S's chest. The vibrators were 6-v. relay coils. When the coil was activated by 110-v. a.c. current, a tempered steel spring was set in vibration at 60 cps. A spherical plastic button was mounted on the armature spring and the button transmitted the vibration to the tactual receptors on S's chest. The rapid switching required for both the discrete visual and vibrotactile displays was accomplished by an electronic voltage comparator. When the voltage representing system error was within 10% of the total range of the input signal, the center light (or vibrator) was activated. Voltages exceeding this on-target range activated one of the other lights (or vibrators) depending on the direction of system error. The input signal, a sinusoid of 5, 10, or 15 cpm, was calibrated to achieve a maximum excursion of ±2 in. on the continuous (CRT) visual display. The control-display sensitivity was set such that control column deflections of ±6.6 deg. were required to match the input voltage.

Procedure.—Both Ss received training on each of the three displays with the 5-cpm input until asymptotic performance was indicated. Both Ss then experienced 20 25-sec. tracking trials on each of the three display conditions with each of the three inputs (single sinusoids of 5, 10, and 15 cpm). The performance metric employed was the integral of the absolute value of system error. Integration was carried out over the final 20 sec. of each 25-sec. trial in order to avoid scoring performance during the initial 5-sec. transient period. The performance metric is identified as average error.

Results and Discussion

The major results of Exp. I are summarized in Fig. 1 where tracking accuracy is shown as a function of input frequency and display mode. Each point in Fig. 1 is the arithmetic mean of 20 25-sec. tracking trials (10 trials per S).

Several important findings are apparent from visual inspection of Fig. 1. First, as shown in previous research (5) performance in this tracking task deteriorates with increases in input frequency for all three display modes. Second, performance with the vibrotactile display is comparable to that with the discrete visual display for an input of 5 cpm. However, for the higher frequency inputs, performance with the vibrotactile display deteriorates relatively more than with the discrete visual display. Finally, there appears to be a constant difference between performance levels on the two visual displays with the continuous display being superior for all input frequencies.

The latter result was expected since a continuous display provides S with information on the direction, magnitude, velocity, and acceleration characteristics of system error, while the three-element display can show S only the direction of error. Since the higher derivatives of system error must be displayed in order that S may anticipate future states of system error, it is not surprising that performance was inferior on displays lacking this information. This, then, could account for the superiority of the continuous display over the discrete visual display, but, one may ask, what could account for the inferior performance levels shown with the vibrotactile display compared to the discrete visual display at the higher frequency inputs? Both displays consisted of three elements, and the same comparator circuit was employed to activate the two discrete displays. Thus, the two modes did not differ in physical characteristics. One might expect that differences in the reactions of the two sensory systems themselves to external stimulation could account for the observed performance differences. However, both the visual and the tactual sensory systems discriminate spatially oriented stimuli, and, further, reaction times to vibratory stimuli are actually shorter than to visual stimuli.

It would appear that past experience may be the critical factor which accounts for the superiority of a discrete visual display compared to the analogous vibratory display. The data contained in Figs. 2 and 3 are quite suggestive of such a conclusion. It may be recalled that prior to the recording of data shown in Fig. 1, both Ss received enough training on all three displays to bring performance to asymptotic performance levels for the 5-cpm input. It is obvious from Figs. 2 and 3 that the amount of such training was least for the continuous visual display, somewhat greater for the discrete visual display, and greatest for the vibrotactile display. Further, with sufficient training S could achieve a performance level on the vibratory display comparable to that with the discrete visual display (see the data of Subject 1, Fig. 2). Thus, there is reason to assume that had sufficient training been given on the vibrotactile display for inputs of 10 and 15 cpm, performance levels could have been brought down to those levels found for the discrete visual display at the same input frequencies.

It is apparent, then, that with only moderate amounts of training a vibrotactile display permits controlling accuracy comparable to that with a (discrete) visual display for inputs with frequency characteristics in the ultra low part of the spectrum (5 cpm or less). For systems subject to inputs of higher frequency,

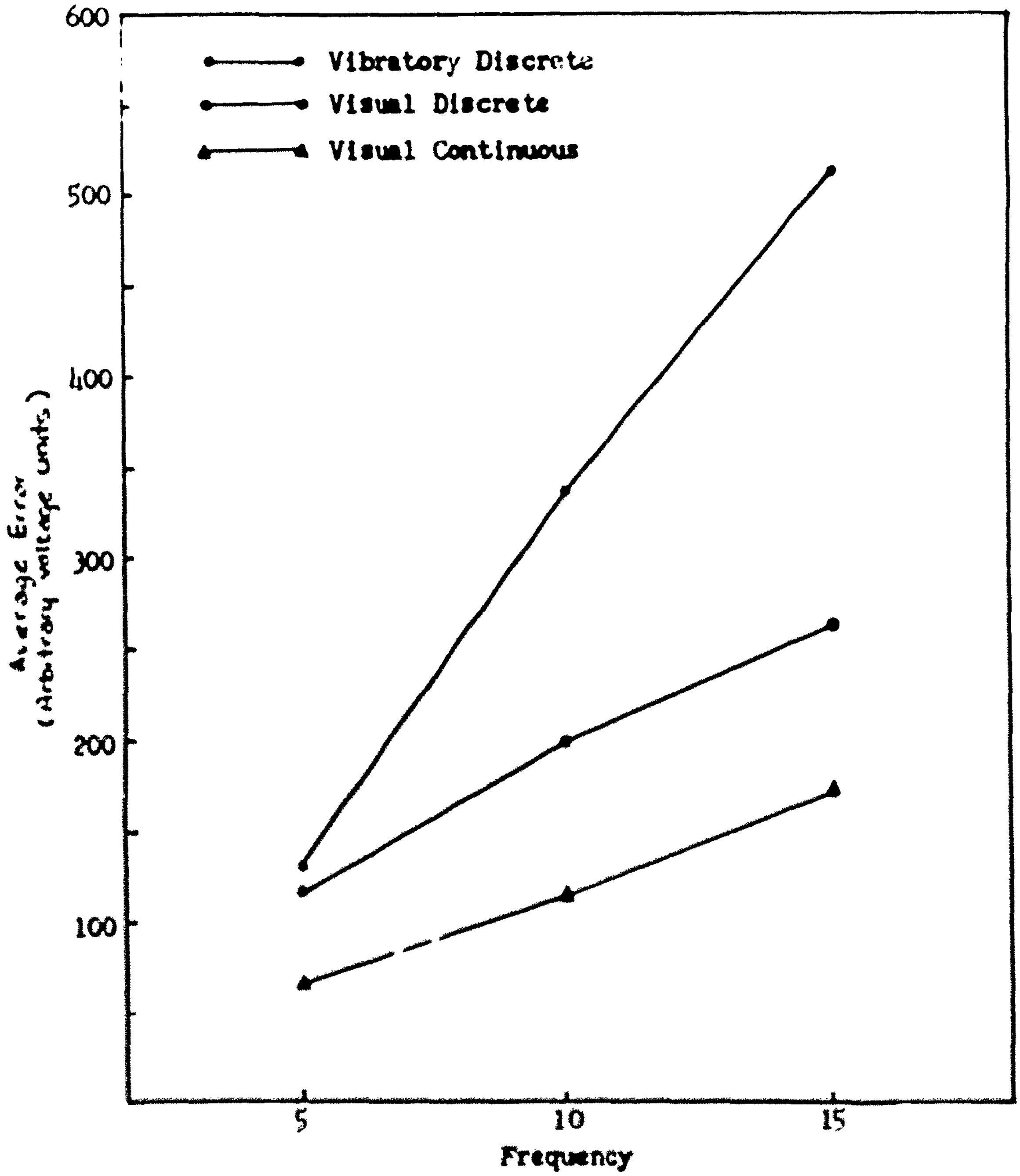


Fig. 1. Tracking error as a function of input frequency for three display modes, Exp. I.

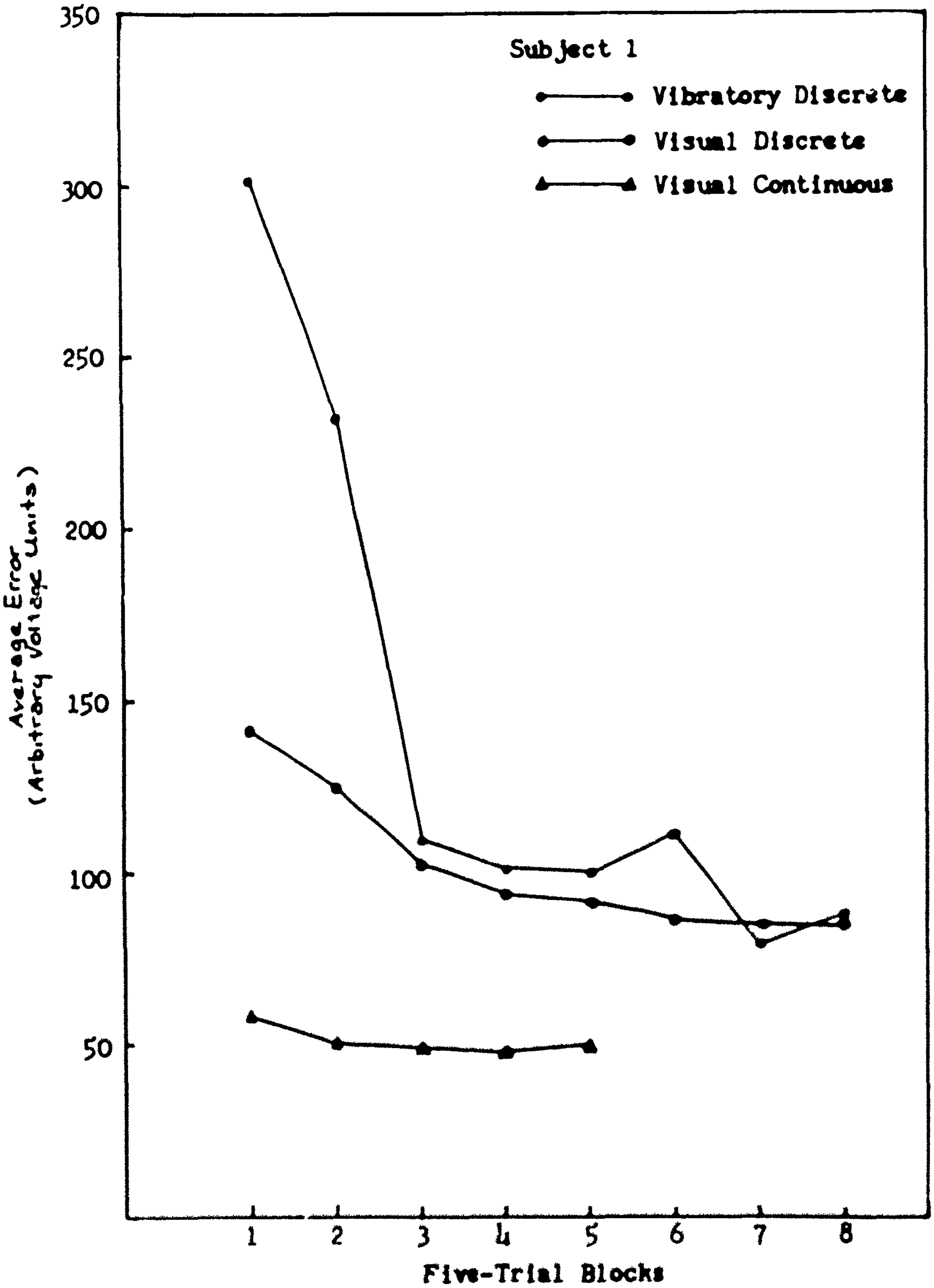


Fig. 2. Tracking error as a function of practice for three display modes (5 cpm input frequency only). Subject 1 of Exp. I.

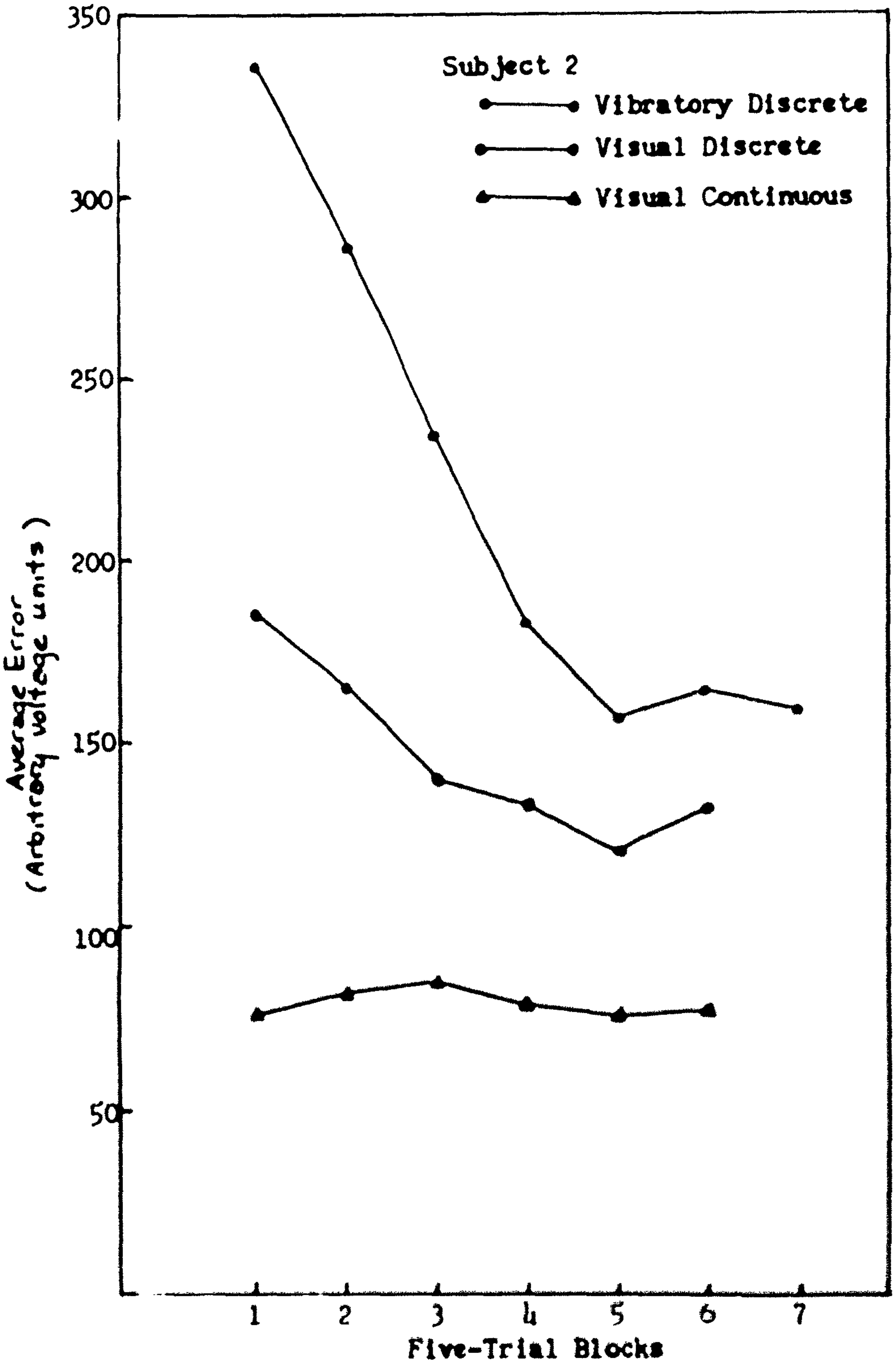


Fig. 3. Tracking error as a function of practice for three display modes (5-cpm input frequency only). Subject 2 of Exp. I.

the vibrotactile display is not a satisfactory mode <u>unless</u> extended training is employed. The present data do not indicate how much training would be required, but it may very well be quite extensive.

EXPERIMENT II

The conditions employed in Exp. I were selected so as to evaluate the vibrotactile display in a most simple control task, one involving no dynamics between the control task, one involving no dynamics between the control column and the information display. This is an unrealistic system since all control tasks involve some dynamics. Further, the conditions employed in Exp. I placed both the vibrotactile and the discrete visual display modes at a disadvantage compared to the continuous visual display. As indicated above, S must estimate higher derivatives in the input signal in order to anticipate future control column displacements. Since the discrete displays provided him only with information relative to the direction of system error, it was expected that accuracy with both discrete displays would be inferior to that with a continuous display which provides S with information not only on direction of system error but on magnitude, velocity, and acceleration aspects as well.

For these reasons, it was desirable to further evaluate the vibrotactile display mode relative to a continuous visual and a discrete visual display in a control system (a) which involves representative dynamics between S's control column and the information display and (b) which removes the need for S to estimate higher derivatives in the input signal.

Method

Subjects.—Four experienced Ss each tracked under a total of 18 display-input control conditions.

Apparatus.—The same control device and information displays studied in Exp. I were employed in the present study. However, here S was required to exercise control through Type II or acceleration dynamics. Thus, whereas a positional deflection of the control column in Exp. I resulted in a change in the position of the cursor (on the continuous visual display), a similar response in the present system would result in a constant acceleration of the cursor (on the continuous visual display). These dynamics were achieved by inserting two analog integrators between the control column and S's information display as shown in Fig. 4a.

In order to relax the requirement that S estimate higher derivatives in the input, the quickening principle (1) was applied to the feedback signal as shown in Fig. 4b. With a quickened feedback system S need base his control column deflextions on only the direction and instantaneous magnitude of displayed error. It was expected, therefore, that a discrete information display could be as effective as a continuous display since directional and a certain amount of magnitude information are apparent on a discrete display as on a continuous presentation.

However, a three-element discrete display can provide accurate magnitude information only if the size of the error signal is near zero. Thus, a second

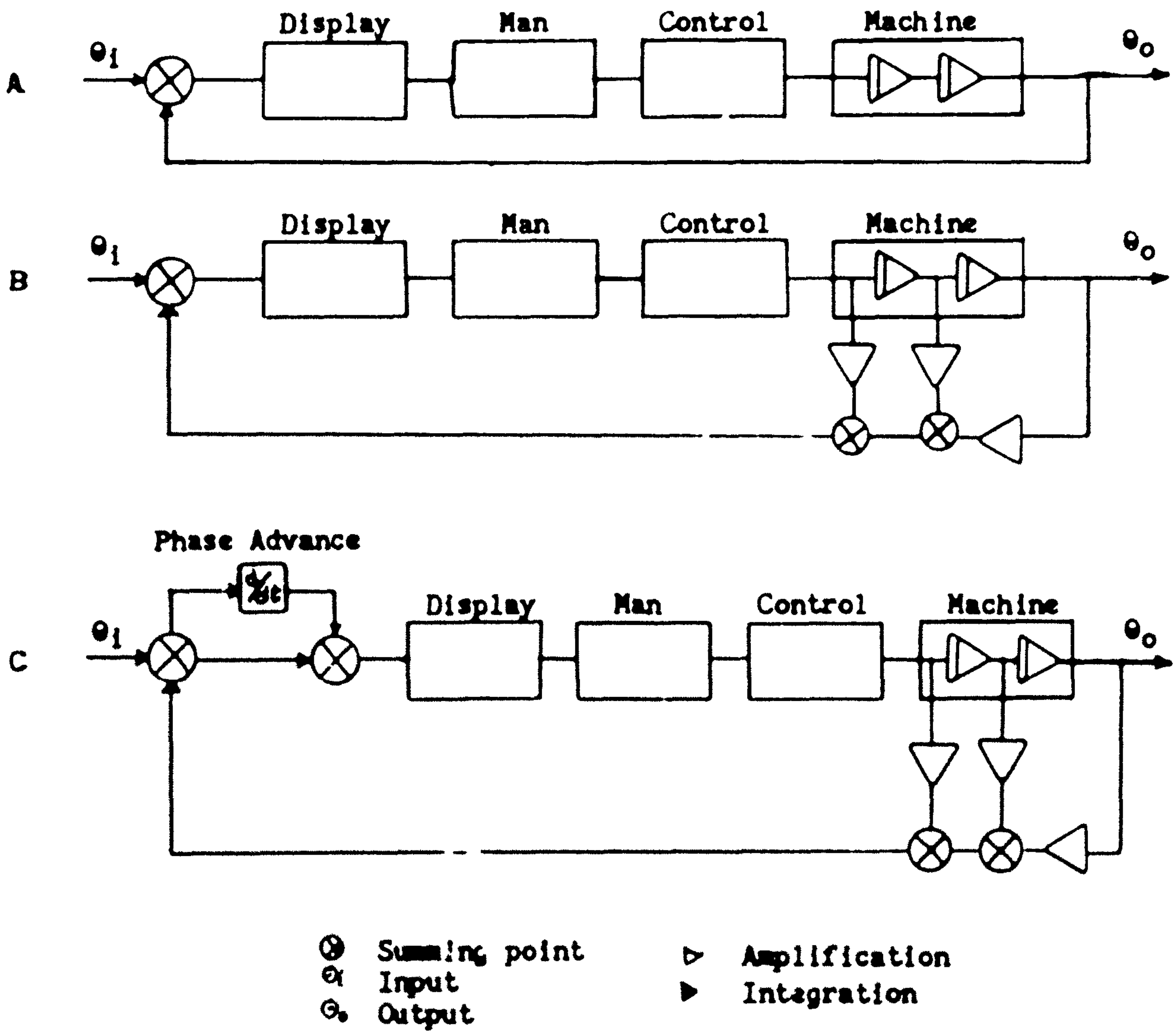


Fig. 4. The tracking system dynamics (a), the quickening of the system (b), and the super quickening procedures (c) employed in Exp. II.

condition was employed which provided a situation in which S was required to base his control column deflections on only the direction of displayed error. Fig. 4c illustrates how this was accomplished. In this condition not only was the feedback signal subjected to quickening, but display aiding was employed also. Thus, by subjecting the error signal to a phase advance transformation, one makes it possible to provide S with all the information necessary to tracking via a simple three-element display as only directional information needs to be considered. Rund et al. (6) refer to the system in Fig. 4c as a super quickened system.

Procedure.—A total of 18 experimental conditions was generated by all possible combinations of three display modes (continuous visual, discrete visual, and discrete vibrotactile), two feedback conditions (quickened and super quickened), and three input signals (single sinusoids of 2, 4, and 8 cpm). Each S received training on each of the 18 conditions until asymptotic performance was attained. Following this, an additional set of 10 40-sec. tracking trials on each condition provided the empirical data. Performance was scored only over the final 30 sec. of each 40-sec. trial. Each S experienced the 18 conditions in a different random sequence to avoid systematic bias in the results.

Results and Discussion

The results of tracking with a quickened display are summarized in Fig. 5, while Fig. 6 contains the results obtained with a super quickened display. As was the case in Exp. I, an increase in input frequency resulted in a deterioration of tracking accuracy for all three display modes. However, the use of quickening and super quickening procedures reduced the differences between the three display modes. This is especially true of super quickening where not only is the relative deterioration of tracking higher frequency inputs via a vibratory display less severe, but also the discrete visual display is comparable to the continuous display at all input frequencies studied.

Thus, it is apparent that, as predicted, quickening and super quickening improve the accuracy of tracking for both the discrete visual and the vibrotactile display relative to that possible with the continuous visual display. Further, a higher level of accuracy is possible with the vibratory display when used in a super quickened system than when employed in less sophisticated control tasks. Since it may be assumed that the operator's control task in a space vehicle will be designed with advanced concepts from both the engineering and human factors point of view, it is apparent that a vibrotactile display could provide an effective mode for the presentation of control information. Again, however, it must be acknowledged that even in a super quickened system, the vibratory display was not particularly effective at input frequencies above the ultra low frequency range (0 to 5 cpm).

EXPERIMENT III

The third and final study in this series was an attempt to explore the usefulness of apparent motion generated with a vibratory display. Apparent motion in the visual mode can be achieved by sequentially activating two or more spatially separated lights. This so-called phi effect is employed widely in advertising. In the present case a comparable experience can be achieved by alternately

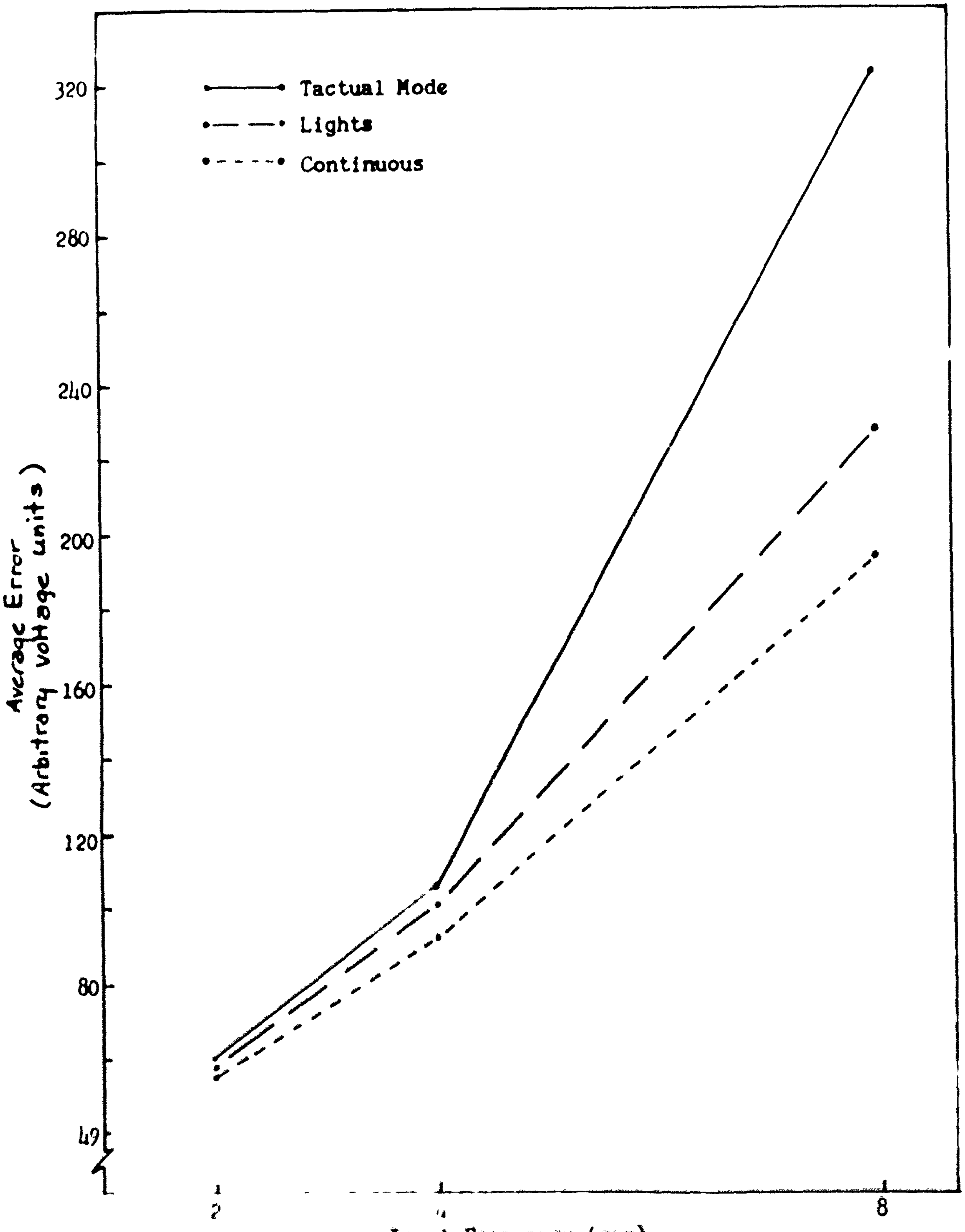


Fig. 5. Tracking accuracy as a function of input frequency for three display modes in a quickened control system. Exp. II.

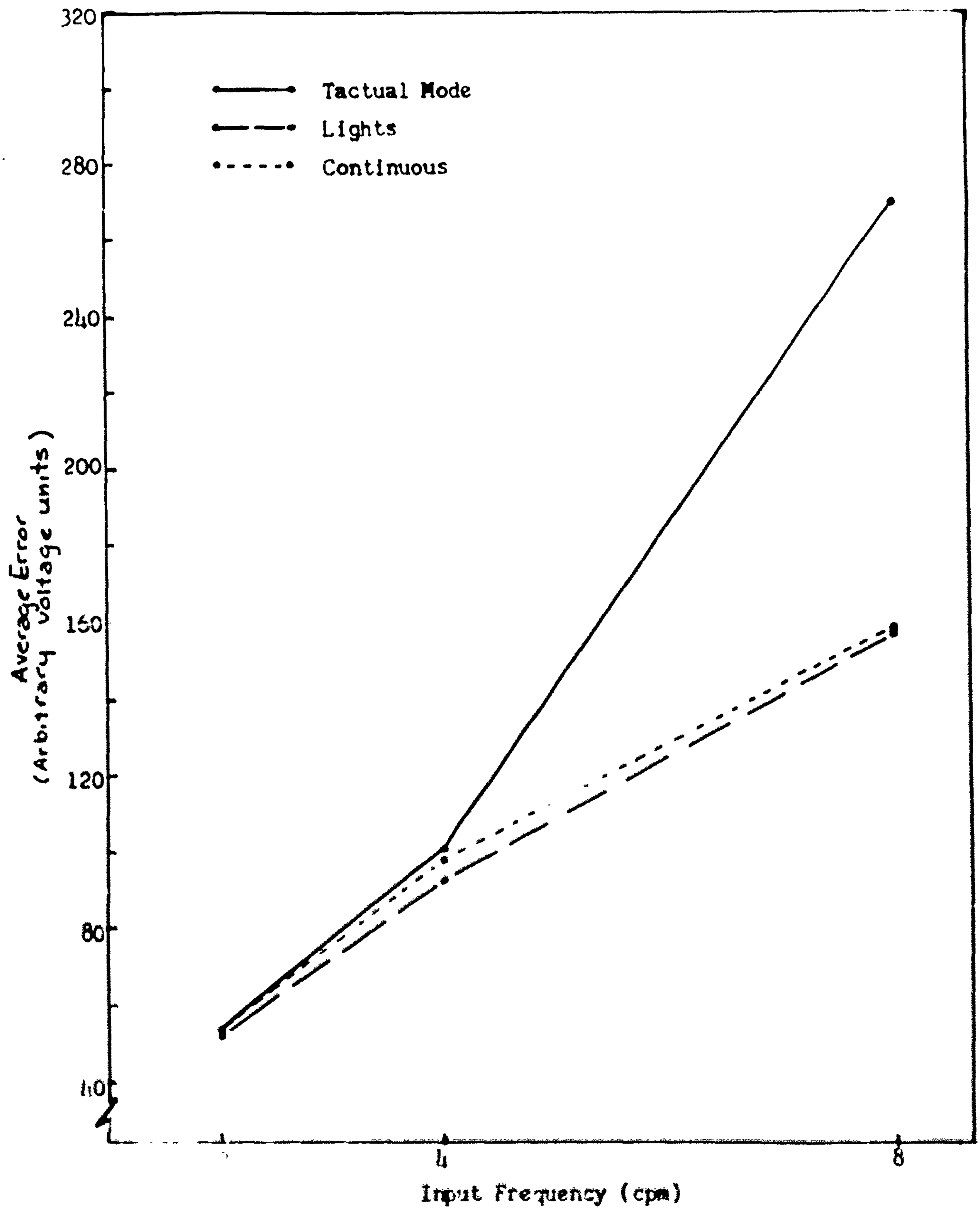
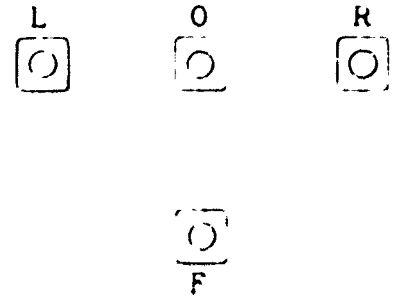


Fig 6 Tracking accuracy as a function of input frequency for three display modes in a super quickened control system. Exp II



(b) Vibrator

Fig. 7. The spatial arrangement of four vibrators to provide the vibratory phi effect studied in Exp. III.

activating two vibrators on the chest. In vibratory phi S experiences apparent movement on the skin between the two vibrators.

In order to provide S with a vibratory phi experience a fourth vibrator was mounted on the lower chest to form a T pattern (see Fig. 7). The vibrator, indicated as F in Fig. 7, was alternately activated with one of the three vibrators R, O, L. If S was "on target," vibrators F and O were activated alternately; if S was off target to the left, vibrator L was alternately activated with F, etc. Thus, S experienced apparent movement across the chest in a vertical direction when on target, and during off-target periods the line of movement was "tilted" to the right or the left depending on the direction of system error.

Method

Subject.—One highly skilled tracker served in this research.

Apparatus.—The same super quickened system utilized in Exp. II was employed in the present study. The same three-element vibratory display employed in both Exps. I and II was used here for comparison with a four-element vibratory display which was designed to provide the vibratory phi effect. In order to produce vibratory phi it was necessary to control accurately the rate of alternation between vibrator F and vibrators R, O, or L (see Fig. 7). One Tektronix waveform generator (Type 162) and two Tektronix electronic pulse generators (Type 161) were used for precise timing. The waveform generator triggered the pulse generators which in turn activated relays which permitted the operation of the appropriate vibrators. The Tektronix apparatus permits one to vary several aspects of the vibratory display. (a) the duration of the individual "bursts" of vibration, (b) the temporal separation between bursts, and (c) the alternating sequence of bursts.

In order to produce Phi, the above three temporal aspects were set as follows. (a) duration of each burst was set at 50 msec , (b) separation between the first and second burst (as between activation of vibrator O and vibrator F in Fig. 7) was set at 25 msec , and (c) separation between pairs of bursts was

set at 25 msec. The necessity to separate the initiation of succeeding bursts in a sequence by 25 msec introduces a transmission lag into the tracking system. Thus, it would not be appropriate to compare the vibratory phi display directly with the three-element vibratory display used earlier in Exps. I and II since that earlier display was lag-free. In order to avoid confounding the effects of phi and the effects of lag, the vibratory phi display was compared to a three-element vibratory display identical to that employed in Exps. I and II with the exception that each vibrator could be activated for only 50 msec. and then all vibration was absent for 50 msec. after which vibration could be experienced for another 50-msec. interval, and so on. This was achieved by removing vibrator F (see Fig. 7) from the display circuitry.

Procedure.--The S received a considerable amount of experience with vibratory phi during the calibration runs which preceded the experiment proper. Following the calibration-training period S tracked a series of 30-sec. trials under eight conditions. The conditions were determined by all possible combinations of (a) display characteristic (a vibratory phi display vs. a three-element vibratory display), (b) display locus (the chest vs. the back), and (c) input frequency (2 cpm vs. 8 cpm). Performance was scored only over the final 20 sec. of each 30-sec. trial and there were 10 trials of data recorded for each of the eight conditions. As in the first two experiments, average error served as the performance metric.

Results and Discussion

The results of Exp. III were essentially negative. As shown in Fig. 8, the vibratory phi display under all conditions was inferior to the three-element vibratory display. Thus, not only was there no advantage to the more "dramatic" presentation via the vibratory phi display, but performance with that display located on S's back was quite inferior to the three-element vibratory display when S attempted to track the 8-cpm input.

An a posteriori explanation of the inferiority of the phi display comes from remarks made by S during the data collection. His comments in comparing the phi display with the three-element vibratory display emphasized the "confusion" introduced by the presence of the fourth vibrator (vibrator F in Fig. 7). The confusion was said to be one of discriminating whether vibrator F or one of the other three vibrators was being activated at a particular time. One of the reasons for this lack of discrimination is that the vibratory transducers employed in this research were rather bulky. Activation of any one transducer tended to spread vibrations over a considerable area of the skin. As long as the display elements (transducers) were arranged along a horizontal line across S's chest, the confusion was minimal. However, when the display took on two dimensional aspects, as in the vibratory phi display, this discrimination decreased and performance deteriorated.

We would not conclude, therefore, that a vibratory phi effect is not a desirable aspect of such displays; rather the effect should be studied further with more compact transducers which exert a more highly localized effect on the skin surface. It is apparent that the chest locus is decidedly superior to a vibratory display applied to S's back.

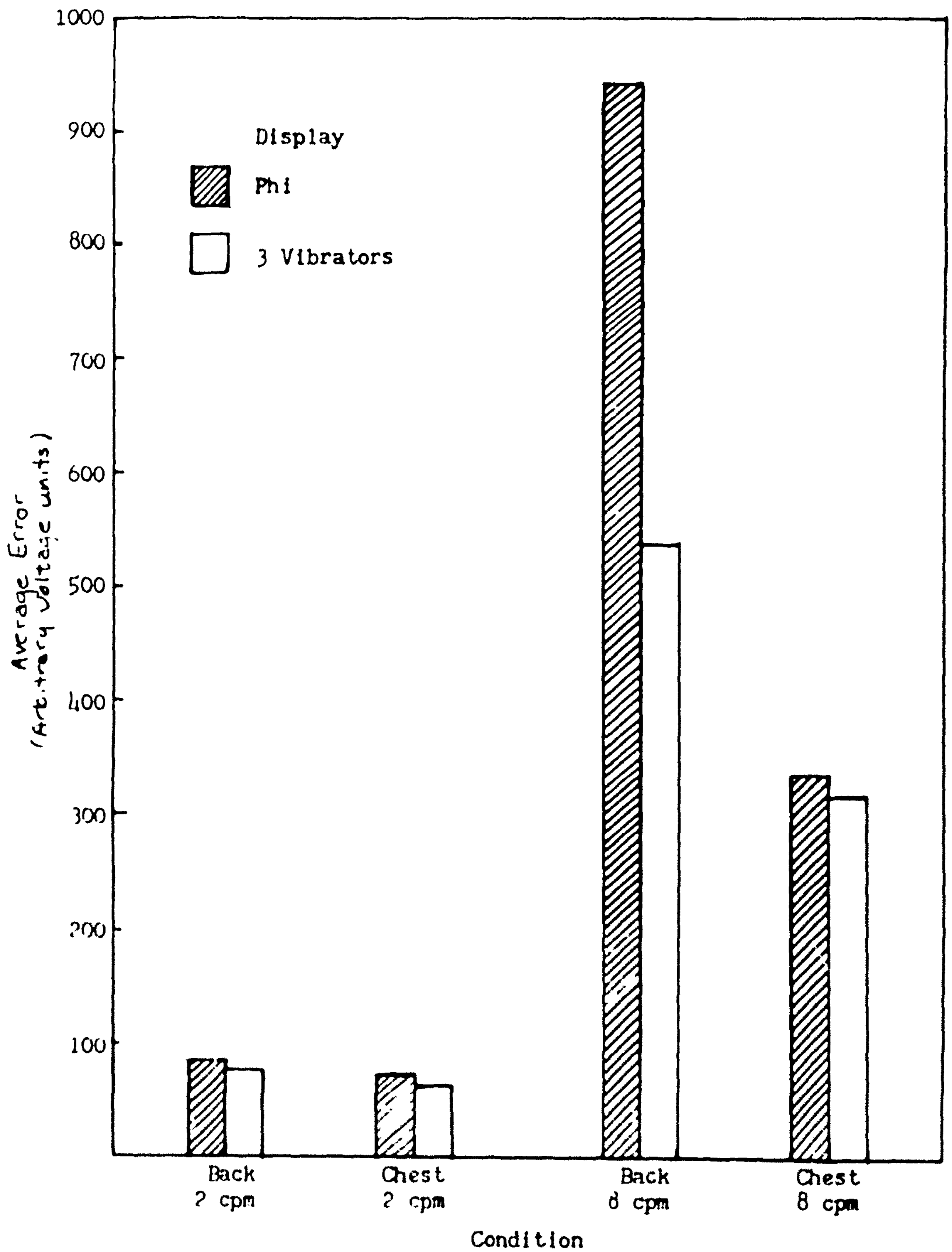


Fig. 8. A comparison of tracking error for a display using vibratory phi with one using three vibrators under two input frequencies and two locus conditions. Exp. III.

SUMMARY AND CONCLUSIONS

Three experiments were completed which explored the accuracy human operators can achieve in both simple and complex control tasks when input and output information are displayed via the tactual sense modality. In the first two studies it was demonstrated that a vibrotactile display can be as effective as a visual display provided the system input is in the ultra low frequency range (0 to 5 cpm). Since humans normally have had little experience with meaningful vibrotactile stimulation, it is necessary to provide the operator with training in control tasks which involve such displays. It is conceivable that with sufficient training the human could adequately control systems with inputs involving frequencies higher than 5 cpm. The present research does not enable one to predict how much training would be required, but it is suggested that the amount would be considerable, especially for higher frequency inputs.

The vibrotactile display was particularly effective when advanced human engineering principles were employed (quickening and super quickening). It is unfortunate that the vibratory phi display explored in Exp. III was not effective since had apparent movement been an effective display feature, the next step would have involved adding a truly advanced human engineering principle to the display circuitry—the Kelley predictor display principle (4). As pointed out in the discussion of Exp. III, however, the failure to demonstrate accurate controlling with a vibratory phi display probably was due to the rather large vibrators employed in this study. Miniaturization of the vibrator elements would be expected to result in a more localized stimulation with a concomitant increase in discriminability between the several elements of the vibrotactile display.

It is concluded, therefore, that a vibrotactile display can be used as a substitute for visual displays in complex control tasks provided (a) the man-machine system is subject to ultra low frequency inputs and (b) the system has been subjected to quickening or super quickening operations. Thus, a vibrotactile mode could be an effective alternate input channel for the processing of input information by the human operator under conditions in which the visual sense is degraded, as in periods of high G stress. It is felt that the above results justify further research on vibrotactile displays under the controlled G conditions provided by a human centrifuge.

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